

Technical Report ARWSB-TR-09003

Material Analysis of Failed Cold-Drawn Billet

**Stephen B. Smith
Edward Troiano
Mark D. Miller**

February 2009



ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
Weapons & Software Engineering Center
Benét Laboratories



Approved for public release; distribution is unlimited.

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

The citation in this report of the names of commercial firms or commercially available products or services does not constitute official endorsement by or approval of the U.S. Government.

Destroy this report when no longer needed by any method that will prevent disclosure of its contents or reconstruction of the document. Do not return to the originator.

REPORT DOCUMENTATION PAGE				<i>Form Approved</i> <i>OMB No. 0704-0188</i>	
<small>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</small> PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) xx-02-2009		2. REPORT TYPE Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Material Analysis of Failed Cold-Drawn Billet				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Stephen B. Smith Edward Troiano Mark D. Miller February 2009				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army ARDEC, WSEC Benét Laboratories, AMSRD-AAR-WSB, B. 40 1 Buffington Street Watervliet Arsenal, NY 12189-4000				8. PERFORMING ORGANIZATION REPORT NUMBER ARWSB-09003	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army ARDEC, WSEC Benét Laboratories, AMSRD-AAR-WSB, B. 40 1 Buffington Street Watervliet Arsenal, NY 12189-4000				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <p>In May 2008, a substrate failure occurred while attempting to explosively clad a Ta10W liner to the inner diameter of a cold-drawn steel tube. Previous cladding operations, using condemned 25mm M242 gun barrels of forged steel, were repeatedly successful. A failure investigation was performed to determine causes for the unexpected fracture of the cold-drawn tube.</p> <p>The failure of the substrate was investigated with a number of materials forensic techniques including fractography, metallography, chemical analysis, mechanical properties testing, etc. The investigation revealed the extremely low toughness of the cold-drawn material when compared to the forged material. The poor performance of the material was exacerbated by welds applied to the substrate during preparations for the bonding process.</p>					
15. SUBJECT TERMS Material Analysis, Failure Analysis, Fracture Analysis					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT U	18. NUMBER OF PAGES 12	19a. NAME OF RESPONSIBLE PERSON
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code)

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Material Analysis of Failed Cold-Drawn Billet

S.B. Smith, E. Troiano, and M. Miller

1. Abstract

In May 2008, a substrate failure occurred while attempting to explosively clad a Ta10W liner to the inner diameter of a cold-drawn steel tube. Previous cladding operations, using condemned 25mm M242 gun barrels of forged steel, were repeatedly successful. A failure investigation was performed to determine causes for the unexpected fracture of the cold-drawn tube.

The failure of the substrate was investigated with a number of materials forensic techniques including fractography, metallography, chemical analysis, mechanical properties testing, etc.

The investigation revealed the extremely low toughness of the cold-drawn material when compared to the forged material. The poor performance of the material was exacerbated by welds applied to the substrate during preparations for the bonding process.

2. Background

The American defense community faces a significant challenge as we develop the next generation cannons for FCS. The requirement for increased range, muzzle velocity, and penetration capability necessitates the development of propellants with increasing energy and flame temperatures. These advanced propellants increase the wear and erosion on medium caliber gun systems. Both current and future Army weapon systems that employ medium caliber cannons will benefit from longer barrel life. In all systems, greater lethality can be achieved with higher-performance propellants. As stated above, these propellants are generally associated with higher flame temperatures and greater erosivity. As an example, the M919 ammunition currently fielded with the M242 cannon erodes the barrel to condemnation in as little as 5000 cartridges though the current requirement is 10000 cartridges, minimum. Introduction of higher performance ammunition into this system results in barrel wear rates not acceptable to the User. Other medium caliber weapon systems including FCS-specific platforms will exhibit similar barrel wear properties.

Through numerous government firing tests including the firing of two 25mm M242 Bushmaster tests in 2001, the use of explosive bonding of tantalum liners in medium caliber barrels has been found to be effective in reducing the wear and erosion of the barrel. Explosive bonding (Figure 1) has been initially demonstrated to produce well-adhered, environmentally-friendly coatings. It is considered

environmentally-friendly in that there is no hexavalent chromium waste stream as generated with the current chromium plating.

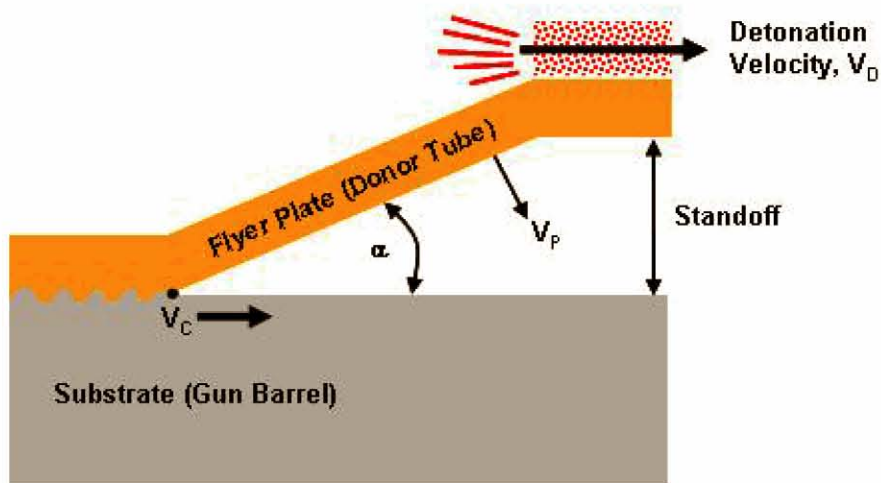


Figure 1: Explosive Bonding Schematic

The 25mm tubes, from which the explosively bonded liners were deposited onto, are traditionally manufactured from forged D6AC steel or cold-rolled D6AC steel as per ASTM 6431. [ARDEC Drawing #12524509, *Barrel, 25mm, Chrome Barrel*] Recently, when explosively bonding a Ta-10W liner from a cold-rolled steel tube – the process suffered a catastrophic failure when the steel significantly fractured during the explosive bonding process. Previous cladding operations, using condemned 25mm M242 gun barrels of forged steel, were repeatedly successful. An investigation was initiated to determine causes for the unexpected fracture of the cold-drawn tube.

Samples of material were sent to Benét Laboratories for analysis. Material samples included sections of the failed tube (CD-001, CD-F1, CD-F2), un-bonded cold-drawn material (CD-002, CD-B), as-received M242 sections (F-M242), and bonded M242 sections (F-M242C). Investigations included alloy composition, phase and grain size analysis, hardness testing, fractography, and mechanical property testing.

3. Data/Observations

3.1. Alloy composition.

Material samples of the CD-001, CD-002, CD-B, and F-M242C substrate steels were drilled from mid-wall of the sample sections. These material samples were tested for carbon and sulfur with a Leco C-S Determinator thermal analyzer. Additional alloying elements were tested via Perkin-Elmer inductively coupled plasma induced atomic emission spectroscopy (ICP-AES). The material samples were compared to the SAE AMS-6431M *Steel, Bars, Forgings, and Tubing, 1.05Cr - 0.55Ni - 1.0Mo - 0.11V (0.45 - 0.50C), Vacuum Consumable Electrode Remelted* standard. This standard is called out on the M242 drawing as D6AC steel.

All the samples tested were within error of the standard.

AMS 6431M (D6AC Low-Carbon Steel)

C/S Tested via Leco Thermal Analyzer, Additional Elements Tested via ICP-AES

Composition (Weight-Percent)

Element	min	max	CD-001	CD-002	CD-B	F-M242C
C	0.45	0.50	0.49	0.48	0.49	0.48
Mn	0.60	0.90	0.74	0.73	0.77	0.70
Si	0.15	0.30	0.22	0.21	0.20	0.17
P	--	0.010	0.01	0.01	0.02	0.03
S	--	0.010	0.0002	0.0002	0.0004	0.0090
Cr	0.90	1.20	0.91	0.89	0.89	0.90
Ni	0.40	0.70	0.49	0.49	0.50	0.45
Mo	0.90	1.10	0.89	0.88	0.92	0.95
V	0.08	0.15	0.09	0.08	0.09	0.06
Cu	--	0.35	0.04	0.03	0.04	0.10

Figure 2: Alloy composition results.

3.2. Microstructure and hardness testing.

Samples of CD-001, CD-002, CD-B, and F-M242 were sectioned, metallographically mounted, polished and etched to reveal the microstructure. Rockwell hardness values were also obtained from the metallographic samples.

All samples showed tempered martensite. The cold-rolled material showed a slightly courser structure, with wider, more dispersed platelets, compared to the forged material. The cold rolled samples also showed a larger grain size. The cold rolled material showed ASTM grain size 5 to 7, while the forged material exhibited a smaller ASTM grain size of 7 to 8.

The slightly courser grain size and structure of the cold rolled material would suggest a slightly lower strength than the forged material. However, the slight degree of difference in the structure of the two materials would not suggest drastically difference performance, as seen in the cladding process.

The Rockwell harness C-scale values of all of the samples averaged 36. Some of the hardness values were below the 36 HRc minimum prescribed in the drawing. The forged material also showed hardness values at the extreme low end of the specification, suggesting hardness did not play a roll in the failure.

Sample	CD-001	CD-002	CD-B	F-M242
ASTM Grain Size #	5-7	5-7	5-7	7-8
Average HR _c	35.4	34.2	37.4	36.6

Drawing specification HR_c 36 to 42.

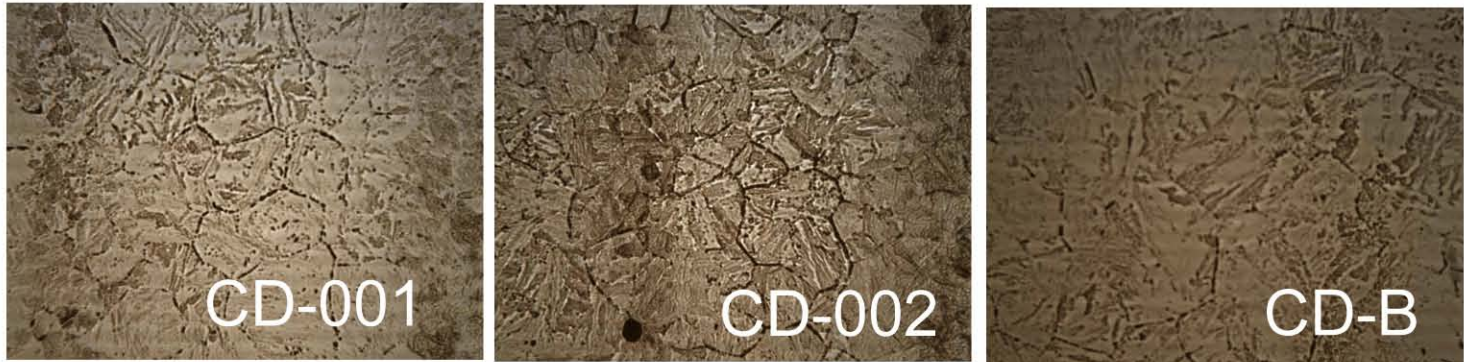


Figure 3: Microstructure and hardness testing. Steel etched with 2% nital.

3.3. Fractography.

Two samples of the failed tube were shipped to Benét, CD-F1 and CD-F2. The fracture faces of the samples were analyzed with optical microscopy for clues to the failure mode.

Sample CD-F1 appears to have come from mid-axis, all sides showed fracture. The failure of this sample originated at the ID at one axial end. The structure of the fracture surface suggests brittle, single-cycle, rapid overload.

Samples CD-F2 was discovered approximately one week after the failure event, exposed to the elements. After receipt at Benét, the sample was subjected to cleaning with a commercial rust remover (Evapo-Rust). CD-F2 is from the end of the tube, one side of the sample was a machined surface. This tube end is where the cladding explosion was initiated. The structure of the fracture surface also suggests brittle, single-cycle, rapid overload. The failure of this sample originated at a number of weld points on the OD and machined surface.

The fractography suggest that the failure initiated at the welds on the end wall and OD of the substrate. Similar welds were used previously during successful bonding of the condemned, forged, tube-material. Although the failure of the cold-formed barrel initiated at the weld-points, similar welding had not caused failure in previous tests, suggesting additional unique characteristics of the cold-drawn material influenced the failure.

- CD-F1
 - Single cycle overload
 - Failure initiated at ID●
 - Secondary axial cracks noted●
- CD-F2
 - Single cycle overload
 - Failure initiated at welds●

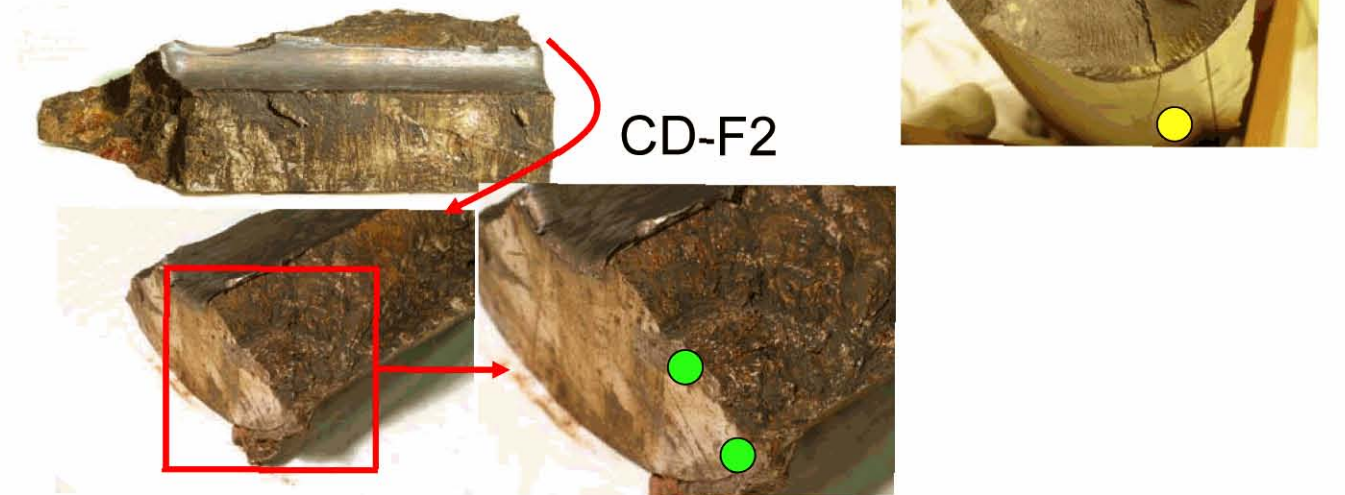


Figure 4: Fractography.

3.4. Charpy testing.

Charpy V-notch impact energy samples were machined from three cold-drawn samples (CD-001, CD-002, CD-B) and two forged samples (F-M242, F-M242C). The samples were removed in the C-R orientation and tested at -40 deg-C.

The three cold-drawn samples, with a 9.0 ft-lb average / 2.18 standard deviation, showed half the absorbed impact energy of the two forged samples, with a 18.5 ft-lb average / 4.24 standard deviation.

Charpy I E	
Sample	I E (ft-lb)
CD-001	6.5
CD-002	10.0
CD-B	10.5
F-M242	21.5
F-M242C	15.5

Test'd @ -40 deg-C

Figure 5: Charpy impact energy data.

3.5. Tensile testing.

Tensile test specimens were machined from three cold-drawn samples (CD-001, CD-002, CD-B) and two forged samples (F-M242, F-M242C). The samples were removed in the C-R orientation, as per ASTM E399, and tested at room temperature, 23 deg-C. The F-M242C sample failed outside the gauge length, and the data generated during testing is not included in this report.

When compared to the forged material sample, the cold-drawn material showed slightly lower yield strength, percent reduction in area, and percent elongation. It also showed a slightly higher ultimate tensile strength.

Tensile Test				
Sample	Y.S. (ksi)	U.T.S. (ksi)	%R.A.	%El.
CD-001	148	178.7	50.3	15.5
CD-002	150	178.9	49.0	16.1
CD-B	152	183.5	44.8	14.6
F-M242	156	173.0	53.1	16.3

Tests performed at room temp (23 deg-C)

Figure 6: Tensile test data.

3.6. Fracture toughness testing.

Tensile test specimens were machined from three cold-drawn samples (CD-001, CD-002, CD-B) and two forged samples (F-M242, F-M242C). The samples were removed in the C-R orientation and tested at room temperature, 23 deg-C.

The cold-drawn material, with an average K_{IC} value of 67 ksi-in^{1/2} / 18.6 standard deviation, showed much less toughness than the forged material, with an average K_{IC} value of 184 ksi-in^{1/2} / 5.7 standard deviation. The load-displacement curve in Figure 6 is particularly telling, as by definition the toughness is the area under the curve. During testing, each of the cold rolled samples resulted in a rapid running crack event while the forged material failed in a controlled, predictable fashion.

Frac. Toughness	
Sample	K (ksi-in ^{1/2})
CD-001	86
CD-002	49
CD-B	65
F-M242	180
F-M242C	188

Test'd @ 23 deg-C

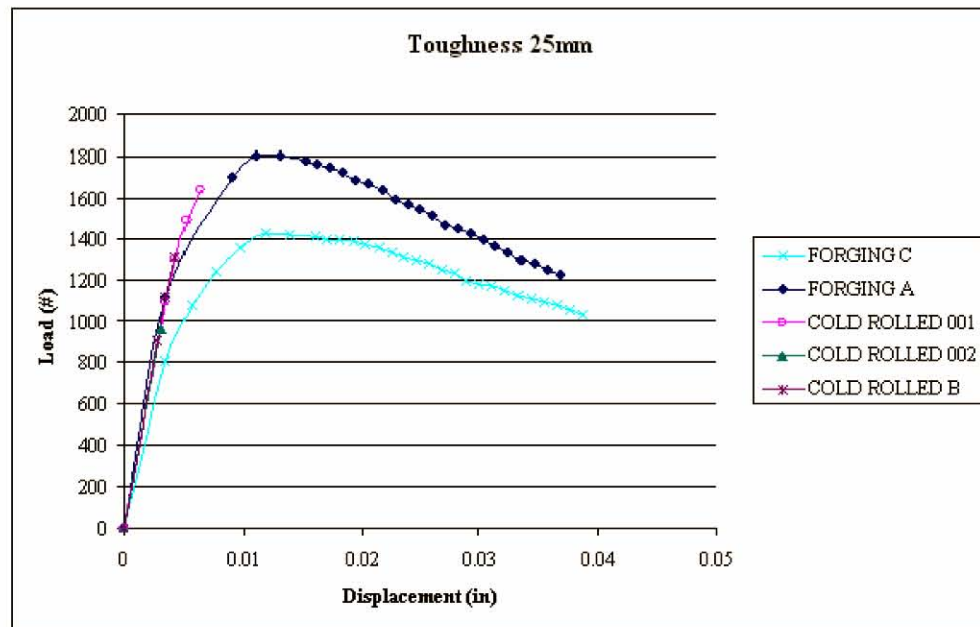


Figure 7: Fracture toughness data.

4. Summary/Recommendations

- The alloy constituents, microstructure, and hardness of the cold-drawn and forged material matched the specifications of the 25mm M242 barrel drawing.
- Fractography suggests the failure initiated at spot weld points on the end wall and OD of the substrate. Due to the presence of these weld points on previously successful forged barrel claddings, the welds cannot be considered the root cause of failure. However, the weld points did appear to exacerbate the poor performance of the cold-drawn substrate.
- Mechanical testing of the material, particularly fracture toughness and Charpy impact energy, has shown that the cold-drawn material has very low toughness when compared to the alternate forged material. The low toughness cold-drawn substrate is unable to effectively contain the high dynamic stresses generated during the explosive bonding process.
- To prevent additional failures during cladding, a minimum fracture toughness value needs to be established. This will allow rather straight-forward mechanical testing of candidate substrate material prior to explosive bonding. A minimum call out according to AMS 6431 is 67 ksi-in^{1/2} at room temperature. This investigation suggests that the 67 ksi-in^{1/2} value is not high enough to ensure the substrate will survive the explosive bonding process intact and unaltered.
- A database of fracture toughness values, particularly in relation to Charpy impact energies, is also recommended. This will enable the inclusion of additional mechanical properties requirements in the barrel drawing, beyond the current hardness requirement.

5. Acknowledgments

The authors would like to acknowledge the technical support provided by Rich Resue, Christopher Rickard, Charles Mossey, and Bob Ronda.